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The Variability of Soils in Earthing Measurements and Earthing System Performance

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Abstract – *The accurate measurement of soil resistivity and earthing system resistance is fundamental to electrical safety. However, geological and meteorological factors can have a considerable effect on the accuracy of conventional measurements and the validity of the measurement methods. This paper examines some aspects of earthing measurements and earthing system performance in the context of both geological and meteorological effects.*

Résumé – *La précision dans la mesure de la résistivité du sol et de la résistivité du système de mise a terre est fondamentale a toute sécurité électrique. Cependant, les facteurs géologique et meterologique peuvent avoir un effet considérable sur l'exactitude et des techniques de mesure conventionnelles et la validité de ces méthodes de mesure. Cet article examine quelques aspects des mesures de mise a terre et de la performance du système de mesure de mise a terre en tenant compte des effets géologique et meterologique conjugues.*

Keywords: Soil resistivity – Earthing system – Electrical safety – Geological and meteorological factors.

1. INTRODUCTION

The earthing of electrical installations is primarily concerned with safety; in particular, the prevention of electrical shock risks to life. As such, an earthing system must be designed, tested and maintained to satisfy this primary aim [1-3].

In the UK, earthing systems are installed in widely differing soil types and geological context, and subject to a range of climatic conditions. As a result of the wide variation in soil conditions across the UK, it is important to obtain an accurate measurement of the soil resistivity. The measurement should be made local to the electrical installation under consideration and the resistivity down to a depth of some hundreds of metres should be determined. Normally, soil resistivity will be measured at the site at the planning stage. The soil resistivity data is used in the calculation to assess the Rise of Earth Potential of the earthing system under earth-fault conditions that enables the determination of the Step, Touch and Transfer Potentials [1-4].

After commissioning of the installation, a test is conducted to measure the actual earth resistance of the completed earthing system. This measured value should correspond to the calculated earth resistance value based on the measured soil resistivity value. It is also necessary to periodically retest this earth resistance in order to check the integrity and continued safety of the system.

If the soil was homogenous and its resistivity unaffected by seasonal variations it would be expected that measured and computed earth resistance values would compare closely. Subject to the maintained integrity of the earthing system, its resistance value would not change. Unfortunately, in practice, the earth exhibits a far from uniform structure. Often, the structure will have horizontal layers related to the physical layers of topsoil, sub-soil, and country rock. There may also be vertical divisions. Accordingly, the assumption of a homogenous resistivity or uniform horizontally layered soil structure is rarely valid in practice. Clearly these layers or divisions in soil structure will have a considerable impact on both soil resistivity and earth resistance measurements of installed earthing systems [5-7].

Seasonal variations will also affect soil resistivity, primarily due to changes in soil moisture content. These dynamic variations may impact significantly on earthing measurements, depending on both the nature of the soil and underlying rock and the type of earthing system.

The earthing standards in the UK [1,2] assume a uniform resistivity equivalent soil model regardless of the geology. Also, no guidelines are given regarding the effect that seasonal variations have on earthing measurements or earthing system performance. This paper reviews present techniques for soil resistivity and earth resistance measurements and examines the effects of spatial and temporal variations in soil.

2. EARTH TESTING TECHNIQUES AND INSTRUMENTATION

2.1. Soil resistivity

Electrical conduction in rocks and soils comprises two basic components. The first is electronic conduction, which is due to the migration of charges through a solid. The second component is due to ionic conduction; this is due to the migration of ionic charges in a polar liquid such as rainwater. Ionic conduction usually predominates and takes place in the filled pore spaces around the grains of a permeable and porous soil or rock [8,9].

In soil resistivity testing, perhaps more correctly called earth resistivity testing, especially where the soil cover is thin, there are several classical electrical measurement techniques [5,10]. As shown in Figure 1, the Wenner technique is commonly used for earth resistivity testing in earthing investigations.

This Wenner technique uses four equally spaced, short electrodes deployed in a single line. Current is passed between the outermost electrodes (C1, C2) and the voltage between the inner two (V1, V2) is measured.

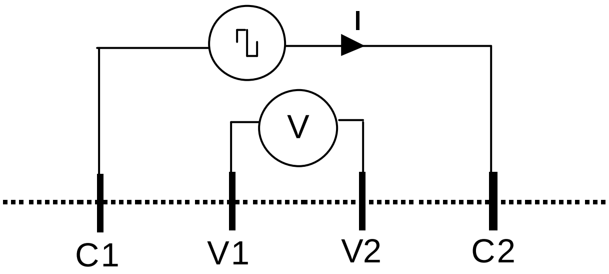

Fig. 1: Wenner configuration

The ratio of this measured potential to the circulated current for a given spacing is known as the apparent resistivity. A number of commercial four-terminal resistance testers are available to perform this type of measurement. The electrode separation can be varied over the range from 0.5 m to several tens or even hundreds of metres, depending on the depth of interest. As the separation is increased about a common midpoint, the apparent resistivity will become influenced by the earth resistivity at greater depths. In performing the Wenner test, it is assumed that the electrodes are small and shallowly inserted and that the earth is horizontally uniform.

The UK electricity industry earthing standard [1] requires the selection of a uniform equivalent soil resistivity model (vertically homogenous as well as horizontally). However, no guidance is given for determining this value from site measurements. The American substation earthing standard (IEEE80) [3] offers more comprehensive guidance concerning resistivity investigations at substations. In this standard, it is acknowledged that soil resistivity varies both laterally and with depth and that seasonal variations may occur due to varying weather conditions.

Accordingly, IEEE80 [3] recommends a uniform soil model only ‘when there is a moderate variation in apparent resistivity’. A number of computer programs are suggested in the standard which are able to derive multi-layer soil models. However, it should be noted that even these multi-layer models assume lateral soil homogeneity.

2.2. Earth resistance measurement

To measure the earth resistance of a large earthing system it is necessary to use the Fall of Potential method [11]. With reference to figure 2, the Fall of Potential (FoP) method uses a four-terminal measurement principle. The earthing system to be measured is attached to one current (C1) and one voltage (V1) terminal, preferably using two separate leads and connectors (Kelvin connections). A remote current electrode (C2) is positioned at a suitable distance from the earthing system under test and a current is circulated between them. This distance, according to the standards, should be at least ten times the maximum apparent dimension of the earthing system [4].

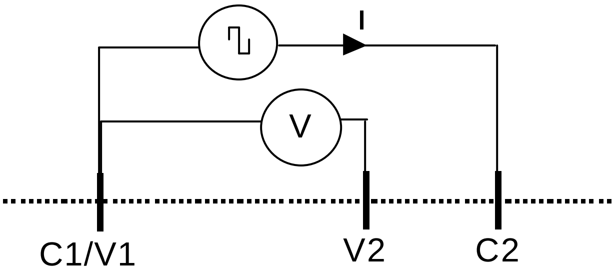

Fig. 2: Fall of potential configuration

To satisfy this criterion for large earthing systems, the C2 electrode may have to be positioned well over 1 km away. The remaining electrode (V2) is placed in line with the C1 and C2 electrodes and the voltage between

V1 and V2 is measured. A series of measurements can be taken by moving V2 over the range from 10% to 90% of the distance from the C1 to the C2 electrode. The ratio of voltage to current plotted as a function of the distance between the V2 and V1 electrodes is known as the Fall of Potential (FoP) curve.

Figure 3 shows a typical FoP curve for a relatively small (100 m^2) earthing system. If the C2 electrode had been positioned sufficiently far away from the earthing system under test, the middle section of the curve would have tended towards a plateau and the resistance of the earthing system under test would correspond to the value of resistance on the plateau. However, when it is impractical to place C2 sufficiently far away the FoP characteristic does not have a definite plateau region. Curdts [11] introduced the ‘61.8% rule’ for obtaining a representative resistance value under these circumstances. However, the rule applies only for homogeneous conditions and concentrated earth electrodes.

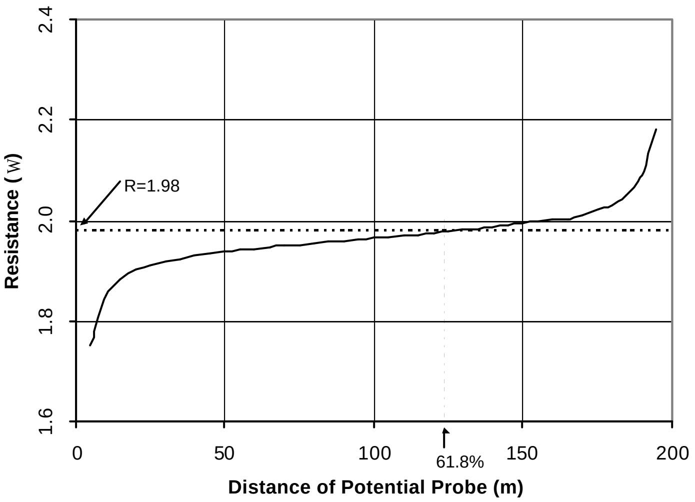

Fig. 3: Fall of potential curve (C2 at 200 m)

2.3. Instrumentation

The test instruments commonly used for earth resistivity and resistance testing are four-terminal resistance meters. These instruments produce a bipolar square-wave current symmetrical about a zero value to avoid polarisation effects. The instruments used should be capable of rejecting power system noise present on an earthing system, or induced into the test leads. It is particularly important to avoid selecting power frequencies for the test signal waveform. Conventional earth testers, such as the Megger DET2/2 [13] use a default switching frequency of 128 Hz but allow the operator to vary this over the range 105 to 160 Hz. Alternative geophysical test instruments, such as the ABEM Terrameter SAS1000, tend to use very much lower switching frequencies (0.25-10 Hz) [14].

As well as the effects of electrical noise from the power system, there are also natural geoelectric fields varying within timescales that can affect electrical earth measurements. Further, there is commonly a standing polarisation between electrodes (Specific Potential) as well as short-term polarisation (Induced Polarisation, especially in clays) caused by the measuring energisation itself. Geophysical instruments, such as the SAS1000, account for these polarisation effects.

3. FFECTS OF GEOLOGY

Apart from occasional outcrops, the country rock found in the UK is covered by soil on top of drift. Generally, soils are the product of weathered and biologically altered country rocks, usually downhill from the source rock, unless significantly affected by glaciation. Some 282-soil types in 67 sub-groups are recognised in England and Wales alone [15]. The country rock, as expected, also has an extremely varied geology and a rich tectonic history being assembled from some 15 terrains [12] and having many thousands of faults, dykes, etc.

As already mentioned in section 2, there is acknowledgement of the non-homogeneous nature of soils and a number of methods are available to produce multi-layer soil models from an analysis of a set of Wenner soundings. However, when resistivity data is interpreted, it may not yield a unique solution [5] to the dimensions and resistivities of the various layers. In practice, a criterion for an acceptable model is for the total rms error between the ‘measured’ apparent resistivity curve and the ‘synthetic’ apparent resistivity curve of the assumed structure falls below about 5%.

Unfortunately, because of the nature of geology in the UK, a model based on horizontal layering, which assumes correspondence with actual horizontal strata will often be erroneous. In practice, many sites will also experience lateral inconsistencies. These may include vertical discontinuities (faults or dykes), vertical divisions (fault-bounded blocks) as well as dipping strata. If the measurement transect crosses a fault, resistivities may be different on each side. Or, a fault may introduce a band of high resistivity as would be the case for an intruded dyke. Lateral variations may also include local anomalies on a small enough scale to affect individual electrodes.

In terms of earth resistance testing, probably the most significant unresolved problem is the effect of vertical divisions in the terrain, i.e. horizontal inconsistencies. These divisions can be occluded and therefore difficult to detect. This makes the correct interpretation of the FoP curve very difficult and, almost certainly, the 61.8% rule would not apply. In addition to general lateral variations, it should be appreciated that most soils and all water migrate downslope (or down dip). Therefore all sloping topography should be expected to have an uneven distribution of both soil and water. This aspect further contributes to making an accurate FoP interpretation more difficult. To assist with the interpretation of FoP curves, borehole data can provide important information about soil structure. However, the interpretation of this data requires detailed geological knowledge.

It is important to recognise that anisotropic properties of soils may also have a significant effect in respect of electrical resistivity. Such effects can exist on both a small-scale (e.g. with clays) and on a large-scale with formations (e.g. with bedding within one rock unit) [9]. Small-scale effects may affect individual electrodes differently, while large-scale effects may affect the overall measurement depending upon the relative alignment of the transect to the formation.

4. FFECTS OF CLIMATE

Probably the most significant short-term changes to soil resistivity are caused by recent weather. It is established that up to saturation, increased water content of any soil or rock will increase its conductivity [8]. Also, the conductivity of soils generally increases with temperature, except in the case of highly metalliferous rocks or soils.

The climatic effects on the electrical properties of soil are mainly restricted to the upper part of the soil, viz. the vadose zone.

4.1. Effects of temperature

Temperature affects both electronic and ionic conductivity. Apart from areas where the geotherm is significant, ground temperature is affected by air temperature and more significantly by insolation. Whilst topography will affect thermal coupling, being highest on windward slopes, it affects insolation even more. South facing slopes, especially with a dark and or rough texture and of sparse vegetative cover, will be subject to most solar heating. Depending upon the type of soil, temperature affects resistivity to a greater or lesser extent [8]. This will be evident on a seasonal timescale but short-term, short-range effects produced by shading might also be significant.

It is interesting to note that freezing inhibits ionic migration; therefore frozen ground will measure with an anomalously high resistivity. Measurements under these conditions are best avoided.

4.2. Effects of water content

It is the moisture content of soils that will have greatest effect on resistivity, especially in the case of porous and permeable soils and rocks. The electrical conductivity of pore water is also significant. Some of the conducting ions in the water are natural to the soil/rock (unless leached out), and some will depend on the conductivity of precipitation (all rainwater is naturally somewhat acid). There will be a contribution due to local effects such as agricultural chemicals, local industrial pollution and salt drift inland from coasts. Salt wind drift can have an effect in excess of 10 km inland, even more in the case of particularly exposed coasts. However, the bulk water content in soil is probably dominates in affecting resistivity.

Most rainfall wets soil from the top down. However, there are some soils that “reverse wet”. A particular example of this is Red Oxford Clay. This soil often develops permanent fissures to a depth of several metres. Surface water can drain into these fissures, hardly wetting the surface layer. At depth, the rainwater diffuses sideways and upwards eventually affecting the water content of the uppermost layer. Reverse wetting is a somewhat similar process to the rise in a perched water table.

There are a number of factors that determine how much of the precipitation actually enters the soil. Of the rain that falls onto an area, some will pond, and some will run off into local surface drainage streams. Some water will temporarily enter the topsoil but will be rapidly lost to the atmosphere again due to transpiration and evaporation. Some will also rapidly drain down to natural or artificial drainage. It is only the remainder that will linger long enough to significantly affect the electrical resistivity of the soil.

Naturally, recent weather conditions will also affect the ‘Water Acceptance Potential’ of a soil. If a soil is already saturated, any further rain will either pond or run off. If the soil has been baked during a long, hot period, it may take a long time for the pores to reopen and allow normal water acceptance processes to re-establish. Long term weather, i.e. climate, will also affect the level of the water table in many places. Most ground surfaces are uneven and will therefore wet unevenly. This will result in small-scale changes in resistivity which can affect both soil resistivity and earth resistance measurements.

If a soil has a good rainfall acceptance potential, an episode of rain will produce a “slug” of water which drains down and diffuses through the various layers of the soil. As this water soaks down through the earth layers, it will affect the resistivity of the different layers in a complex way. It complicates the apparent layering of the soil model which may be difficult to establish from surface measurements alone.

In addition to natural changes in moisture and water table, the effects of human activities can also be significant. Examples of this which affect the water table level are (i) adjacent commercial gravel abstraction, which involves significant water pumping and lowers the local water table (ii) water abstraction from perched aquifer by a distant pumping station.

5. CONCLUSIONS

This paper has shown that both spatial and temporal changes could occur during measurements on scales that may significantly affect results. Further, in order to be able to use retest results for the condition assessment of an earthing system, repeatability needs to be good. This is somewhat doubtful and field experience bears this out. Perhaps UK standards for earthing systems and their testing need to be revised in order to take into account both weather and geology. It has also shown that the performance of an existing earthing system may be adversely affected by climate, and that this is likely to be geology dependent. It may even be beneficial for site geology, etc, to be taken into account in any initial design.

Earth resistivity measurements use shallowly inserted measurement electrodes, typically < 0.5 m, to determine the resistance of deeper layers. The surface soil is essentially being used as an interface to measuring the electrical resistivity of deeper structures. Earth resistance measurements use similar electrodes. This implicit reliance on such a fickle substance may not be fully justified.

In this brief review, it has been demonstrated that the effects of geological and seasonal variations in soils have a considerable impact on the electrical characteristics and therefore can affect earthing system performance. It has also been demonstrated that a multi-disciplinary approach to earthing should benefit the subject. Certainly there are aspects of geophysics and geology that would usefully complement the traditional purely electrical engineering approach. What is somewhat disappointing is that effects of weather and geology have for so long been ignored. Perhaps it can be shown that under all combinations of such conditions the effects on measurements and performance are negligible. If this is indeed the case, well and good, it will maintain the present simplicity of approach. However, in order to be able to confidently disregard such effects, their magnitudes must first be properly quantified and so far this does not appear to have been adequately done.

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